

Recent Increases in NO_x Emissions from Coal-Fired Electric Generating Units Equipped with Selective Catalytic Reduction

Thomas F. McNevin

*New Jersey Department of Environmental Protection, Trenton, NJ, USA
Please address correspondence to: Thomas F. McNevin, NJDEP, Division of Air Quality, 401 East State St.,
PO Box 420, Trenton, NJ, 08625-0420, USA; email tom.mcnevin@dep.nj.gov*

The most effective control technology available for the reduction of oxides of nitrogen (NO_x) from coal-fired boilers is Selective Catalytic Reduction (SCR). Installation of SCR on coal-fired electric generating units (EGUs) has grown substantially since the onset of the US Environmental Protection Agency's (EPA) first cap and trade program for oxides of nitrogen in 1999, the Ozone Transport Commission (OTC) NO_x Budget Program. Installations have increased from 6 units present in 1998 in the states which encompass the current Cross-State Air Pollution Rule (CSAPR) ozone season program, to 250 in 2014. In recent years, however, the degree of usage of installed SCR technology has been dropping significantly at individual plants. Average seasonal NO_x emission rates increased substantially during the Clean Air Interstate Rule (CAIR) program. These increases coincided with a collapse in the cost of CAIR allowances, which declined to less than the cost of the reagent required to operate installed SCR equipment, and was accompanied by a 77% decline in delivered natural gas prices from their peak in June of 2008 to April 2012, which in turn coincided with a 390% increase in shale gas production between 2008 and 2012. These years also witnessed a decline in national electric generation which, after peaking in 2007, declined through 2013 at an annualized rate of -0.3%. Scaling back the use of installed SCR on coal-fired plants has resulted in the release of over 290,000 tons of avoidable NO_x during the past 5 ozone seasons in the states which participated in the CAIR program.

Implications: To function as designed, a cap and trade program must maintain allowance costs that function as a disincentive for the release of the air pollutants which the program seeks to control. If the principle incentive for reducing NO_x emissions is the avoidance of allowance costs, emissions may be expected to increase if costs fall below a critical value, in the absence of additional State or Federal limitations. As such external factors as the cost of competing fuels and a low or negative growth of electric sales may also disincentivize the use of control technologies, the continuation of desirable emission rates will be best maintained by the implementation of performance standards that supplement and complement the emissions trading program.

Introduction

The Clean Air Act Amendments of 1990 (CAAA) required substantial reductions in emissions of sulfur dioxide (SO₂) and oxides of nitrogen (NO_x). NO_x reductions were to be effected through the adoption of NO_x RACT (Reasonably Available Control Technology), which called for control of “major stationary sources of oxides of nitrogen” in ozone nonattainment areas and in the Ozone Transport Region (OTR).

The Ozone Transport Commission (OTC), a multi-state entity created under the Clean Air Act Amendments to coordinate regional development of control plans for low-level ozone for the Northeast and Mid-Atlantic States, developed a program to control NO_x emissions from major stationary sources in the OTC Ozone Transport Region during the May 1 - September 30 ozone season. An initial cap and trade “NO_x Budget Program” for ten Northeast states, developed in 1994 and effective in 1999 (U.S. Environmental Protection Agency [EPA], 2009a), was replaced by the subsequent EPA “NO_x SIP Call” NO_x Budget Program, which expanded the program to a total of 22 eastern states in 2003-04 and lowered the existing caps (EPA, 2011). Together these measures incentivized the installation of selective catalytic reduction (SCR) control equipment, a technology capable of over 90% reduction in NO_x emissions, on 19% of eastern U.S. coal-fired electric generating units (EGUs) by 2008. These programs were then succeeded by the Clean Air Interstate Rule (CAIR) in 2009 (EPA, 2014a), which was to be replaced by the 28-state Cross-State Air Pollution Rule (CSAPR) in 2012 (EPA, 2014b). Due to various legal rulings, CAIR remained in effect through 2014, to be succeeded by CSAPR, which commenced on January 1, 2015.

Within the affected states, NO_x emissions declined substantially from their 1990 baseline levels. Examination of EPA’s Air Markets Program data reveals that emissions declined on average by 52% by the onset of the OTC NO_x Budget Program in 1999, due to RACT-driven burner modifications, along with a combination of old unit closures and resultant load shift to new cleaner units, generally gas-fired combined cycle units. In continuing these activities, some states’ ozone season NO_x emissions declined further during the trading program, resulting in an overall reduction of 60% from baseline levels by 2002. Increased installations of SCR on coal-fired EGUs also contributed to this decline, (EPA, 2009a; EPA AMPD).

Following the onset of the NO_x cap and trade programs, substantial numbers of coal-fired EGUs installed SCR (SCR Coal). Ozone season emission rates for these units were generally at their lowest in the early to middle years of the “NO_x SIP Call” program, 2005 – 2006, after which they began trending upwards.

Upward movement of NO_x emission rates increased substantially during the CAIR program which began in 2009. This movement coincided with a collapse in the cost of CAIR allowances, which was accompanied by a decline in delivered natural gas prices from their peak in June of 2008, which in turn coincided with a substantial increase in shale gas production during the period. National electric generation also declined in those years, which after peaking in 2007, declined through 2013 at an annualized rate of -0.3%.

CAIR featured both an annual and an ozone season (May – September) cap and trade program. While most states were in both the annual and seasonal programs, some were selected to be in one or the other. Among the top 25 EGU ozone season NO_x emitters in the states that participated in the CAIR ozone season program, which make up most of the eastern half of the United States, the number of EGUs with installed SCR, i.e., the most effective technology for NO_x reduction, increased from 1 in 2008 to 14 in 2014.

Methodology

Emissions data for NO_x from the EPA's Air Markets Program Data tool (AMPD) were analyzed for the 16 ozone seasons through the duration of the three multi-state NO_x cap and trade programs from 1999 through 2014. These began with the Ozone Transport Commission (OTC) NO_x Budget Program for the OTR northeast and Mid-Atlantic states in 1999, followed by the "NO_x SIP Call" NO_x Budget Program for the included OTR states in 2003 and an additional 11 in 2004 for a total of twenty eastern states, and the Clean Air Interstate Rule (CAIR) in 2009, which added all or part of several additional states. Emission trends were compared with production and cost figures of natural gas along with data on electrical generation from the Energy Information Administration (EIA), and with emission allowance cost figures for the three cap and trade programs.

Discussion

Since the passage of the CAAA (1990), the implementation of NO_x RACT (1995), the OTC NO_x Budget Program (1999), and the "NO_x SIP Call" NO_x Budget Program (2003-04), the number of coal-fired boilers in the electric generation sector with SCR has increased steadily, from the nation's first 3 installations which began operations in New Jersey in 1994, to 30% of the Eastern US coal fleet in 2014, as illustrated in [Figure 1](#). Based on emissions data provided by the US EPA's Air Markets Program Data tool, the lowest observed emission rates on such units were, in general, achieved in the years immediately following the full implementation of the "NO_x SIP Call" cap and trade program in 2004, ([Figure 2](#)). Since that period, there has been a general upward movement in average seasonal NO_x emission rates of coal-fired, SCR-equipped (SCR Coal) EGUs, along with corresponding increases in emissions, which accelerated rapidly after 2010, (EPA AMPD).

[Figure 2](#) depicts a count of all existing SCR Coal units, within the states that participated in the CAIR ozone season program, that were in existence in each year from 1999 to 2014, along with their seasonal emission rate averages. The average ozone season NO_x emission rates depicted during the OTC program years are elevated because they reflect a wide variety of operations both within the OTR states along with units coming on line in the non-OTR CAIR states which were not yet under a cap and trade program and together were not being fully utilized. The onset of the "NO_x SIP Call" trading program saw both the largest year-to-year increases in numbers of units with installed SCR, and the largest decrease in region-wide average NO_x emission rates from those units. For many individual units, optimum, average seasonal best

observed rates (BOR) of NO_x emissions tended to occur in the early to middle years of the “NO_x SIP Call” Program, after which rates began to drift upwards.

This upward trend in NO_x average seasonal emission rates is most clearly shown in examination of the SCR Coal EGUs that appear among the top 200 NO_x emitters in the region in the final year of each program, ([Figure 3](#)). In the first two programs, rates came down within the targeted states once the programs got underway, stabilizing at lower levels after the first year or two. However, with the CAIR program, there was an almost linear year-to-year increase in state-wide emission rates of these SCR-equipped, coal-fired EGUs. While state-wide rates show the depicted increases, results are varied with individual EGUs.

Through the years of the CAIR program, emission rates among the SCR Coal units in the top 200 NO_x emitting units doubled. The ratios of individual 2014 ozone season emission rates of SCR Coal units with respect to their BORs range from 1.0 to 9.2, with a mean of 3.3. While some units are operating essentially at their BOR, other units have reverted to emission rates comparable to that seen prior to SCR installation, ([Table 1](#)). As more SCR Coal units operated at increasing NO_x emission rates with each passing year, the number of such units which moved into the higher cohorts of individual NO_x emitters increased concurrently. It is this increase in emission rates that account for the numbers of SCR Coal units that have increasingly appeared among the top ranked NO_x emitters over the past 7 ozone seasons, ([Figure 4](#)).

Generally, BORs occurred in the first year or two after SCR installation. For many EGUs this was in the 2002 to 2005 range as many SCR Coal Units were installed at that time, in anticipation of the “NO_x SIP Call” Program, ([Figures 1, 2, and 3](#)). As new SCR installations have continued with each year however BORs for some units have come in later years. The average BOR year for the SCR Coal Units in the 2014 Top 200 was 2007.

Four factors contributed to this degradation in performance over the CAIR period: decrease in allowance costs, decrease in the cost of natural gas, increase in ammonia costs, and decrease in electric demand.

Allowance Costs. Possession of an allowance authorized the holder to emit 1 ton of NO_x. In the first year of the OTC NO_x Budget Program, which ran from 1999 to 2002, allowance prices ranged in pre-season trading from \$1,500 to \$3,000 before spiking to over \$6,500 amid market uncertainty about possible allowance shortages. As confidence improved in 1999, prices settled down to a range of \$600 to \$1,700, generally less than \$1,000, for the duration of the program, (OTC, 2003; Fraas, A.G., and N. Richardson, 2010).

While average seasonal emission rates of SCR Coal units during the OTC NO_x Budget Program were generally well above what the technology was capable of delivering, ([Figure 3](#)), it was common for units to finish the ozone season with excess allowances. Allocations were distributed to sources from the EPA Clean Air Markets Division, through the states, based on a 55% or 65% reduction from 1990 baseline levels, depending on the defined Zone in which an OTC region state was located, (OTC, 1994). Because earlier NO_x RACT burner modifications had reduced emissions substantially below 1990 levels, installed SCR was employed to varying degrees by different facilities. They were generally however not required

to be operated at maximum potential in order to avoid exceedance of the allocations that were given to each unit, and the resultant implicit costs.

Allowance costs during the “NO_x SIP Call” Program, (2003 – 2008), ranged from a high of \$8,200/ton at the onset of the program to a low of \$593/ton after the program ended, (Argus Air Daily). Trading continued after the May-September 2008 ozone season as banked allowances from this program still had value as they could be carried over into the following CAIR program. Average value for an allowance throughout the “NO_x SIP Call” program was approximately \$2,000/ton, (Argus Air Daily). Allocations to SCR Coal units were provided based on heat inputs from prior years at a rate of 0.15 lb NO_x / mmBTU, (40 CFR 96.42). Based on the cost of purchasing allowances, it was desirable to operate SCR sufficiently as to not surpass the allocations provided at this rate. Optimal operation of SCR provided surplus allowances that could either be sold profitably or transferred to other units within the same company that emitted in excess of 0.15 lb/mmBTU. The balance between available allowances and emissions was quite close through most years of the program, finishing in the final year with emissions 9% below the 2008 cap. Allowance prices fell in this final year of the program. (EPA 2009a; EPA AMPD).

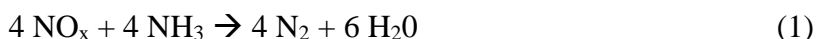
CAIR, (2009 – 2014), consisted of both a seasonal and an annual program. A ton of NO_x emissions during the ozone season had to be covered by an allowance from both the seasonal and annual programs. Total costs for these combined allowances ranged from a high of \$6,650/ton at the onset of the CAIR program in January 2009, to less than \$100/ton by August 2011, a value that was not exceeded for the remainder of the program through December 2014, (Argus Air Daily).

In addition to the 275,367 banked allowances that were carried over into CAIR from the previous program by companies and facilities (EPA 2009a), EPA also made available to the program 199,997 allowances as a Compliance Supplement Pool, (CFR § 97.143), the availability of which was determined on a state-by-state basis. The availability of these additional allowances resulted in a substantial surplus of allowances with respect to ozone season emissions throughout the program.

Increase in Natural Gas Production. Production of natural gas in the United States, has increased dramatically in recent years with the implementation of hydraulic fracturing in the Marcellus Shale in the eastern United States, as well as other formations elsewhere in the country, (USEIA, 2015). As production rose, gas prices fell, thus becoming increasingly economically competitive with coal for electrical generation, ([Figure 5](#)). As such, the fraction of gas-fired generation increased substantially, while that of coal decreased, ([Table 2](#)). US shale gas production rose from 2,116 billion cubic feet (bcf) in 2008 to 11,415 bcf in 2013, a 5.4-fold increase, which contributed to a 17% rise in overall US gross production through the same period, (USEIA, 2015a). After peaking at \$12.41/thousand cubic feet (mcf) in June 2008, the electric power price of natural gas declined to a low of \$2.81/mcf in April 2012, at which point, the first ever parity between gas and coal-fired generation occurred with each providing 32% of US generation. While the price of gas increased since then to \$4.22/mcf as of October 2014, the price was still down -66% relative to the 2008 high.

With this more recent gas price increase, however, coal-fired generation increased 4.6% in 2013 relative to 2012, (USEIA, 2015c). Nonetheless, gas-fired generation has made substantial gains against coal-fired electrical generation in recent years, as noted in [Table 2](#), wherein gas has increased from 21% of national generation in 2008 to 28% in 2013, while coal has fallen from 48% to 39% through the same period.(USEIA, 2015b,c). Most of this increased gas-fired generation has come from combined cycle turbines, from both new construction and from increased use of existing units. Due to both the decrease in coal use and the increase of the much lower emitting combined cycle units, overall seasonal NO_x emissions have declined, even as NO_x emissions from SCR curtailment on coal has increased through the period, (EPA AMPD).

Ammonia Costs. Reduction of NO_x by ammonia is given by the simplified NO_x equation:



As the net stoichiometry is approximately 1:1, essentially 1 ton of ammonia is required to reduce 1 ton of NO_x. In SCR, anhydrous ammonia, or a 19% - 29% aqueous solution is injected into flue gas ahead of a catalyst bed consisting of heavy metal oxides or zeolites, (EPA, 2002). Urea, which is safer to handle, is used by some operators in place of ammonia.

Ammonia costs during the OTC NO_x Budget program generally ranged from \$100 to \$200/ton. Ammonia was cheaper than emission allowances during those years, yet most coal-fired facilities did not need to push their installed SCR to its maximum potential. While ammonia costs averaged about \$340/ton during the “NO_x SIP Call” program, this was still considerably cheaper than the average allowance cost of approximately \$2,000/ton, (USGS, 2015, Argus Air Daily).

In recent years, during the CAIR program, ammonia costs have averaged about \$470/ton (USGS, 2015). Based on this variable cost alone, allowance costs in a cap and trade program covering the emission of one ton of NO_x lose their ability to encourage ammonia-driven emission reductions when they cost less than the reagent used to operate the installed equipment.

[Figure 6](#) displays the combined CAIR allowance prices, (seasonal and annual), for an EGU emitting at 3.0 lb NO_x / MWh, which is a rate typical of a boiler with NO_x RACT-induced combustion modifications such as Low NO_x Burner Technology, (LNBT), which has no operating SCR. Also shown is the approximate cost of ammonia in \$ / MWh. As the cost of allowances to cover emissions decreases below the cost of the ammonia feedstock required to reduce them, market forces act to encourage rather than discourage emissions. Further impetus in this direction is provided by the declining price of natural gas used in competitive electrical generation. As gas and allowance costs declined, the average seasonal NO_x emission of rates of the SCR Coal units found within the top 200 emitting units in the 2014 ozone season more than doubled from 2009 through 2012.

Decline in Electric Demand. Electrical generation and resultant NO_x emissions are also affected by current and forecast electric demand, which in turn effects wholesale pricing of electricity, and the likelihood that at a given production cost, a particular generating unit will be dispatched,

(called upon to supply power to the grid). From 2000 through 2007, US electrical generation grew at a typical annualized rate of 1.3% ([Figure 7](#)). Peaking in 2007, generation by 2013 has subsequently decreased at an annualized rate of -0.3% (USEIA 2015b). Electrical generation, indicated by gross load figures, (GLOAD), reported to EPA, by the 94 SCR Coal units among the top 200 emitters in the 2014 ozone season had an annualized decrease in generation of -2.7% for the same 2007 – 2013 period, (EPA AMPD). Reduced generation decreases income to the generator from electric sales which may incentivize a corresponding effort to reduce expenses.

State-to-State Variations. Emissions may be regulated to achieve reductions in three general ways. A technology-specific, or design standard, a maximum allowable emission rate performance standard, or, a market-based cap and trade approach in which a source is given an allotment of allowances consistent with the reduction goal and is free to address its operations as it see fit as market forces act to minimize costs and reward innovation. (AQMUS, 2004).

Average statewide emission rates for SCR Coal units that were operating in the 2014 ozone season in the western states that were outside of the CAIR program boundaries were seen to be uniformly indicative of optimum SCR operations, ([Figure 8](#)). As no cap and trade program was in effect for these states, it is evident that emissions are restricted with operating permit limitations which derive from design, and/or performance standards.

Similarly, state-level restrictions effectively, if not explicitly, requiring continual SCR use exist within some of the states participating in the CAIR program, as evidenced by their SCR Coal 2014 ozone season emission rates. The rates, shown from low to high in [Figure 8](#), indicate a range of behaviors. Clearly, within the CAIR program states, market forces in some cases have acted to engender increases in emissions, rather than their decrease. The higher numbers displayed in [Figure 8](#) illustrate substantial curtailment of SCR use in the majority of SCR Coal units in those states. In some cases (Pennsylvania, New York), curtailment occurred in all operating units. [Figure 9](#) illustrates the year-to-year increases in NO_x emissions due to this curtailment among the CAIR states, which occurred counter to the overall trend of declining NO_x emissions that was previously noted.

Summary

Substantial reductions in NO_x emissions from large stationary sources, i.e, electrical generating units, have been achieved across the country since the Clean Air Act Amendments of 1990. In addition to burner modifications, fuel switching, and retirements, which have been particularly noteworthy among coal units in the past decade, hundreds of other coal units installed SCR. In recent years reductions in NO_x emissions have also been facilitated by a reduction in coal use and a corresponding increase in gas-fired generation

During the “NO_x SIP Call” NO_x Budget Program, when allocations were not present in excessive quantities, and costs remained at sufficiently high levels to encourage the operation of installed pollution control equipment, most SCR Coal units showed their lowest seasonal emission rates. Under the CAIR cap and trade program, excess of allowances, and

correspondingly low prices encouraged the acquisition of emission allowances preferentially to the operation of installed SCR, as the cost of allowances fell beneath the cost of the reagent required to operate the equipment. Market forces thus incentivized increases in emissions. In plants that were not prohibited from curtailing SCR operations by operating permit limitations, emissions dramatically increased through the period. As a result, upwards of 290,000 tons of additional, avoidable NO_x were released in the CAIR states during the 2010 – 2014 ozone seasons. Emission increases at these plants were further encouraged by the decline in natural gas prices, which incentivized competitive gas-fired generation, and a decline in electric sales, which reduced income to the generators. Other plants which had requirements in their operating permits, that implicitly or explicitly required the use of installed SCR, continued to operate with low emissions at optimum rates. Hence, in recent years in states that were wholly reliant on the cap and trade program for reductions, emissions were not reduced as effectively as occurred in states which had supplemental performance standards in place.

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About the Author

Thomas F. McNevin is a Research Scientist in the Bureau of Air Quality Planning, Division of Air Quality at the New Jersey Department of Environmental Protection, Trenton, NJ.

Tables

Table 1. Representative individual EGU comparisons of pre-SCR Installation NO_x Emission Rates, (lb NO_x /mmBTU), with BORs, 2014 Ozone Season Rates, and 2014/BOR ratios

Unit ID	Pre-SCR Installation	Best Observed Rate	2014 Rate	2014 / BOR
	Rate Year	Rate Year		
9943	0.337 2003	0.047 2005	0.150	3.2
31223	0.397 2000	0.087 2005	0.370	4.2
39442	0.478 1998	0.066 2005	0.372	5.6
31492	0.381 1998	0.047 2003	0.411	8.7
60042	0.355 2002	0.039 2005	0.367	9.4

Table 2. Percentage of US Annual Electric Generation by Fuel Type.

Fuel	2008	2009	2010	2011	2012	2013
Coal	48%	44%	45%	42%	37%	39%
Natural Gas	21%	23%	24%	25%	30%	28%
Other	31%	33%	31%	33%	33%	33%

Figures

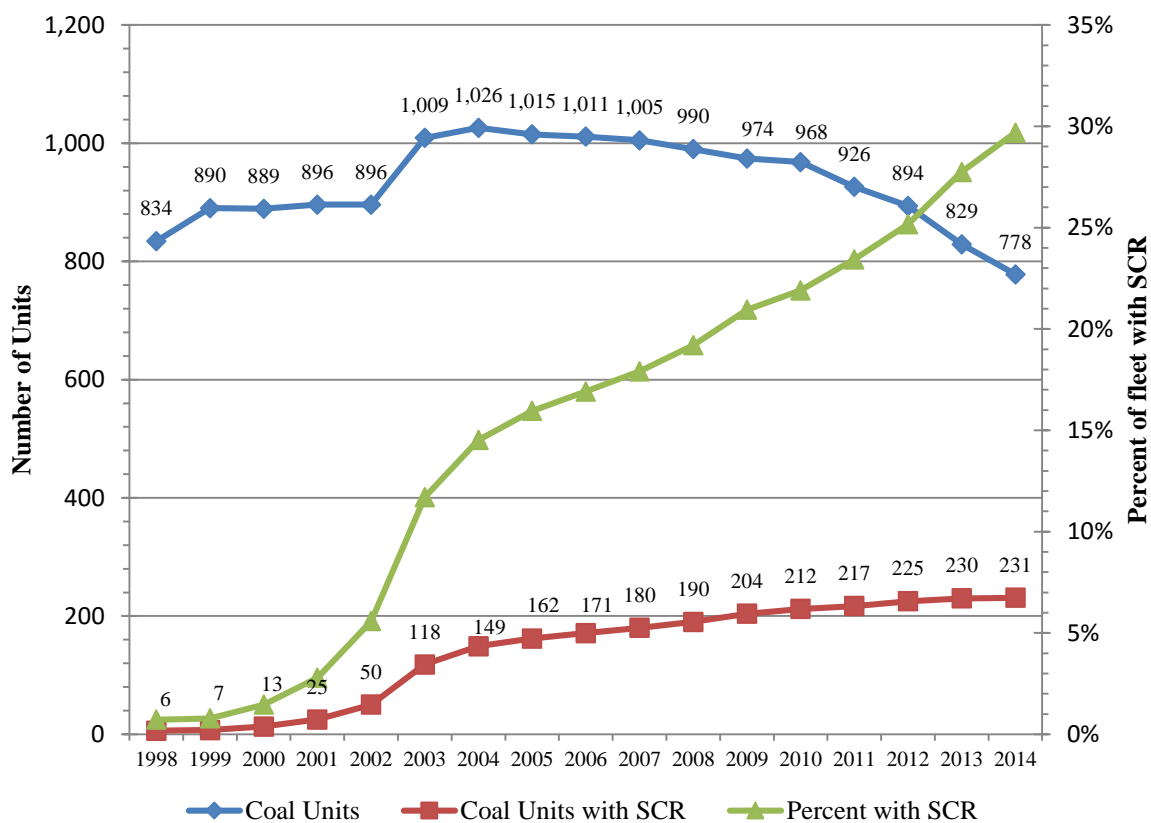


Figure 1. Total number of coal-fired EGUs and the number and percent with installed SCR in each year in CAIR states.

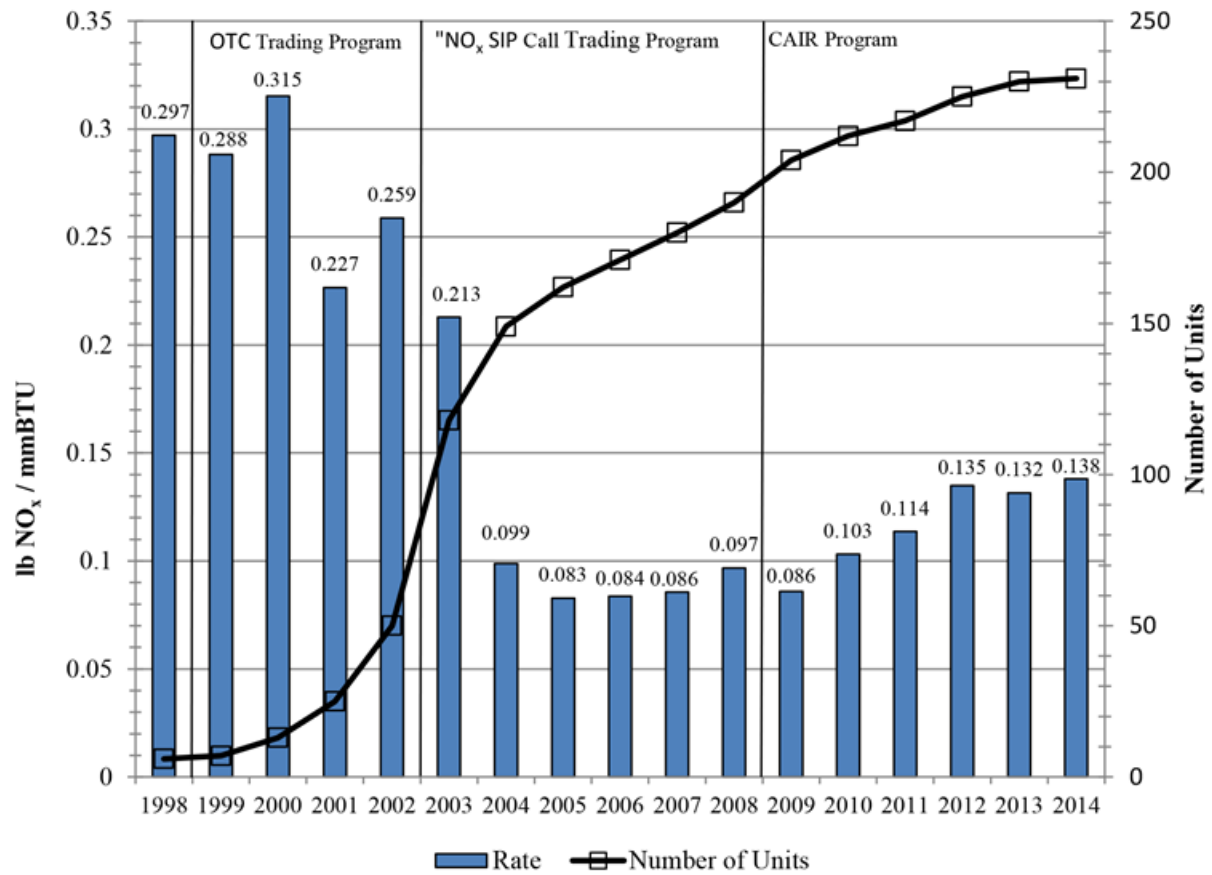


Figure 2. Ozone Season CAIR States NO_x Emission Rates of SCR-Equipped Coal-Fired EGUs with number of Units.

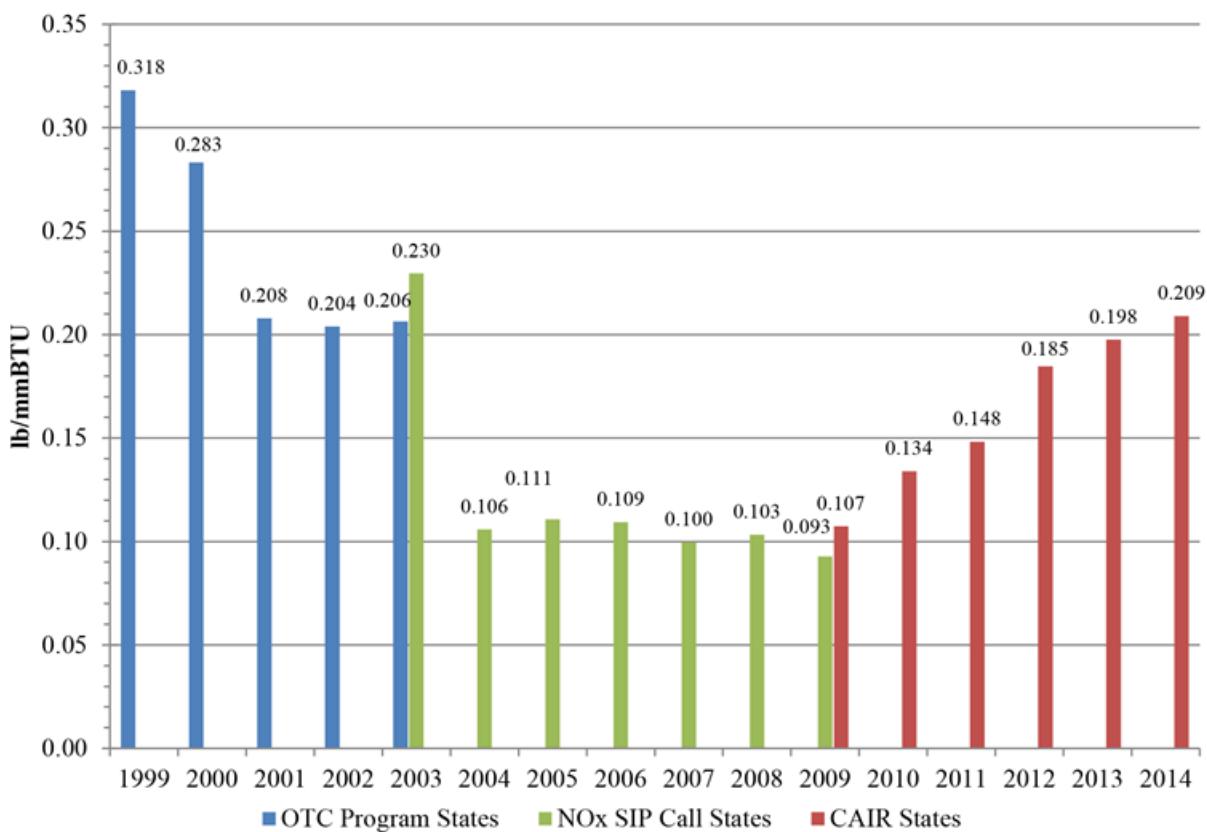


Figure 3. Average Ozone Season Emission Rates of Coal-Fired, SCR-Equipped EGUs among the Top 200 NO_x Emitters in each of the 3 Cap & Trade Programs over 16 years.

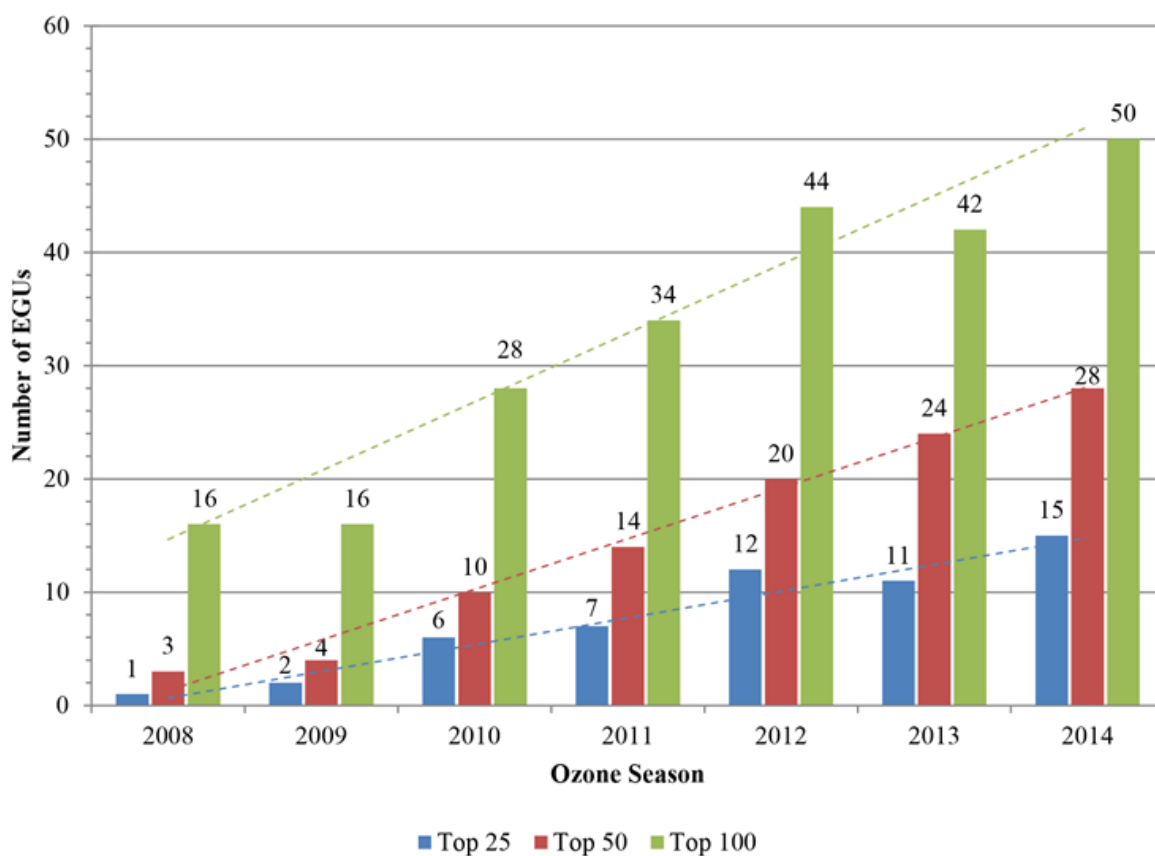


Figure 4. Numbers of SCR Coal units found among the top cohorts of CAIR states NO_x-emitting EGUs in the 2008 - 2014 ozone seasons.

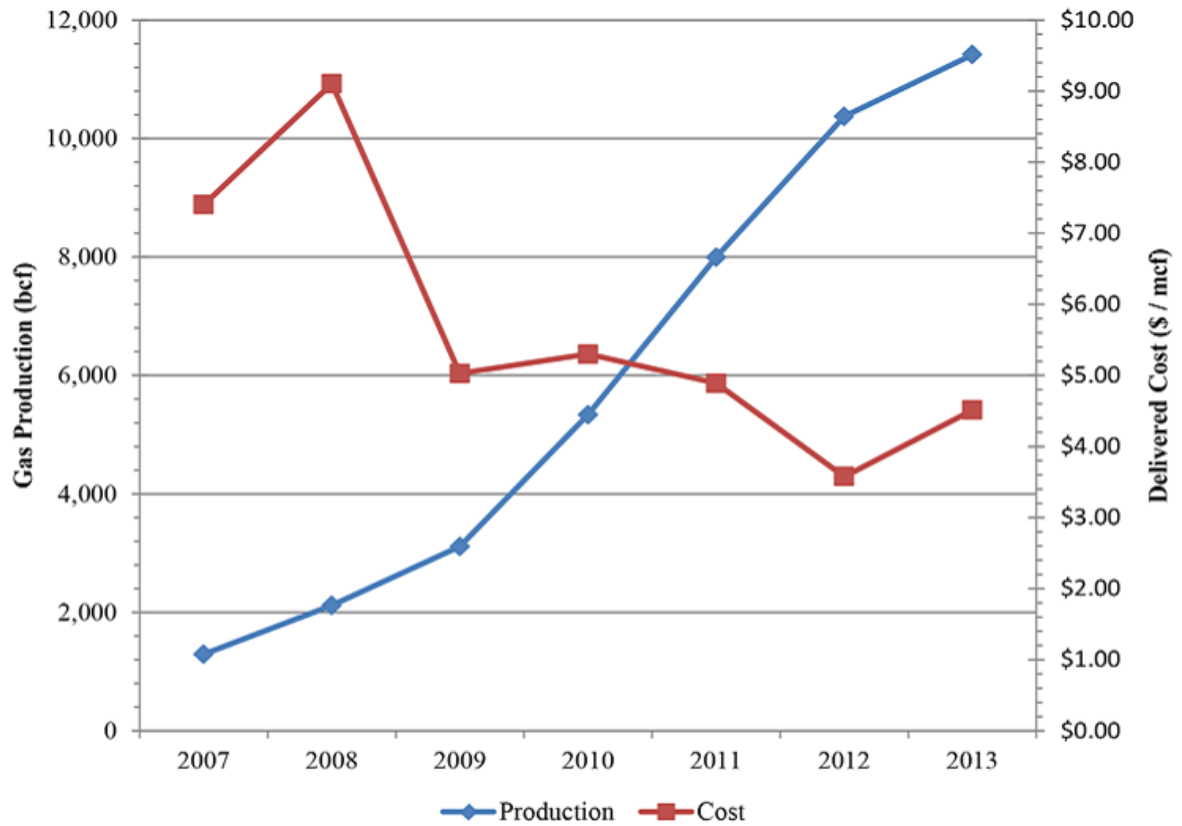


Figure 5. Production of shale gas and annual average delivered gas cost for electrical generation, 2007 – 2013.

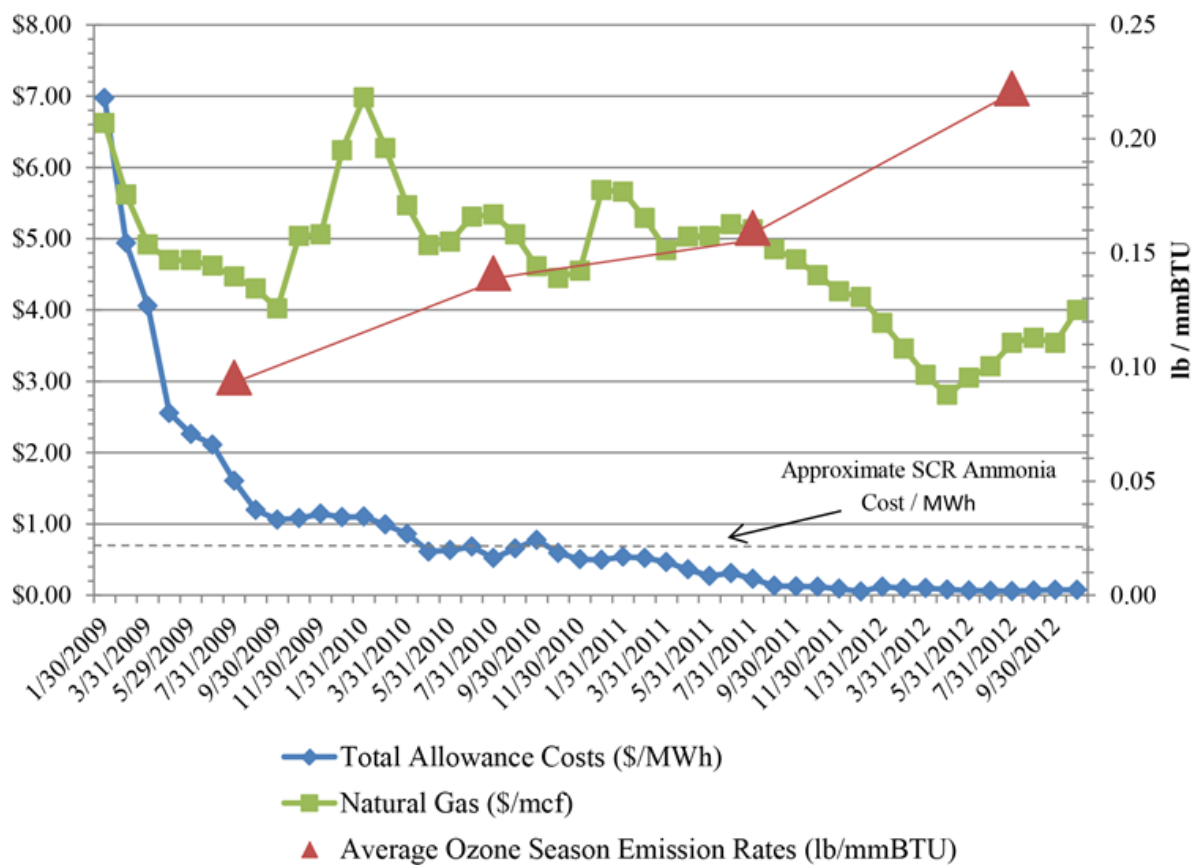


Figure 6. Total monthly average ozone season allowance costs at 3.0 lb NO_x / MWh, with monthly average natural gas electrical generation costs, and average ozone season emission rates.

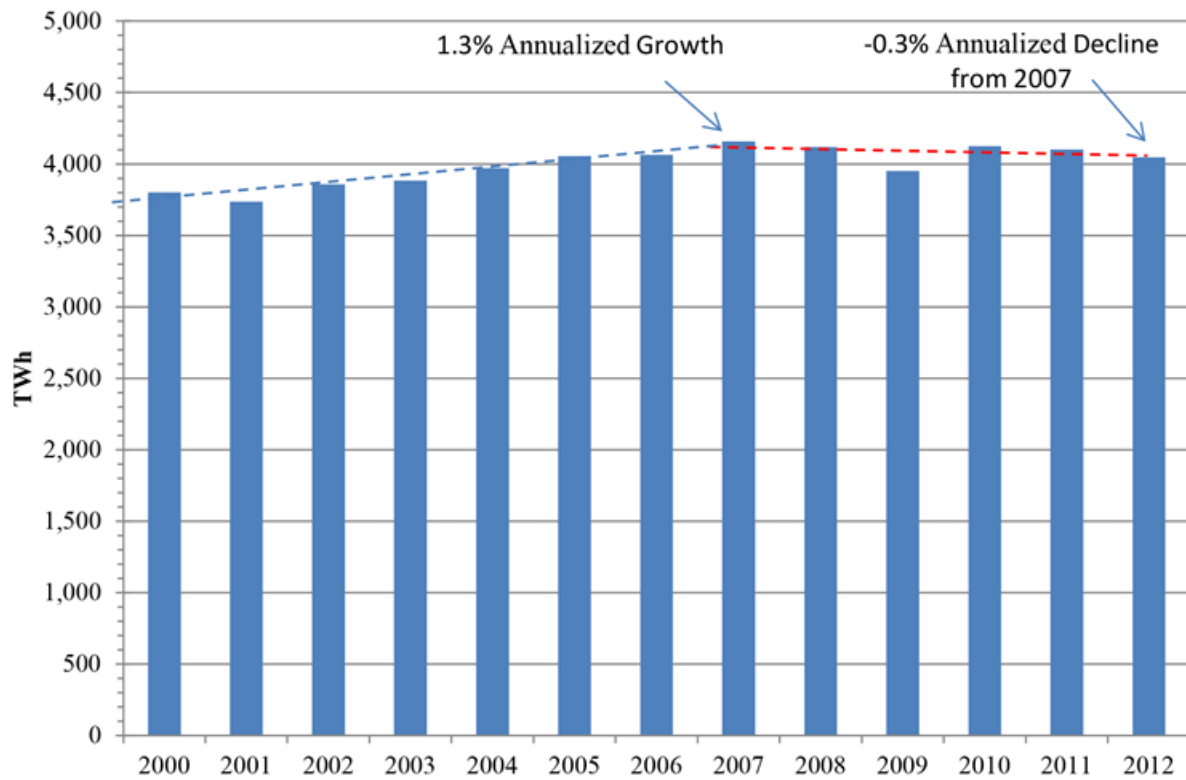


Figure 7. US net electric generation.

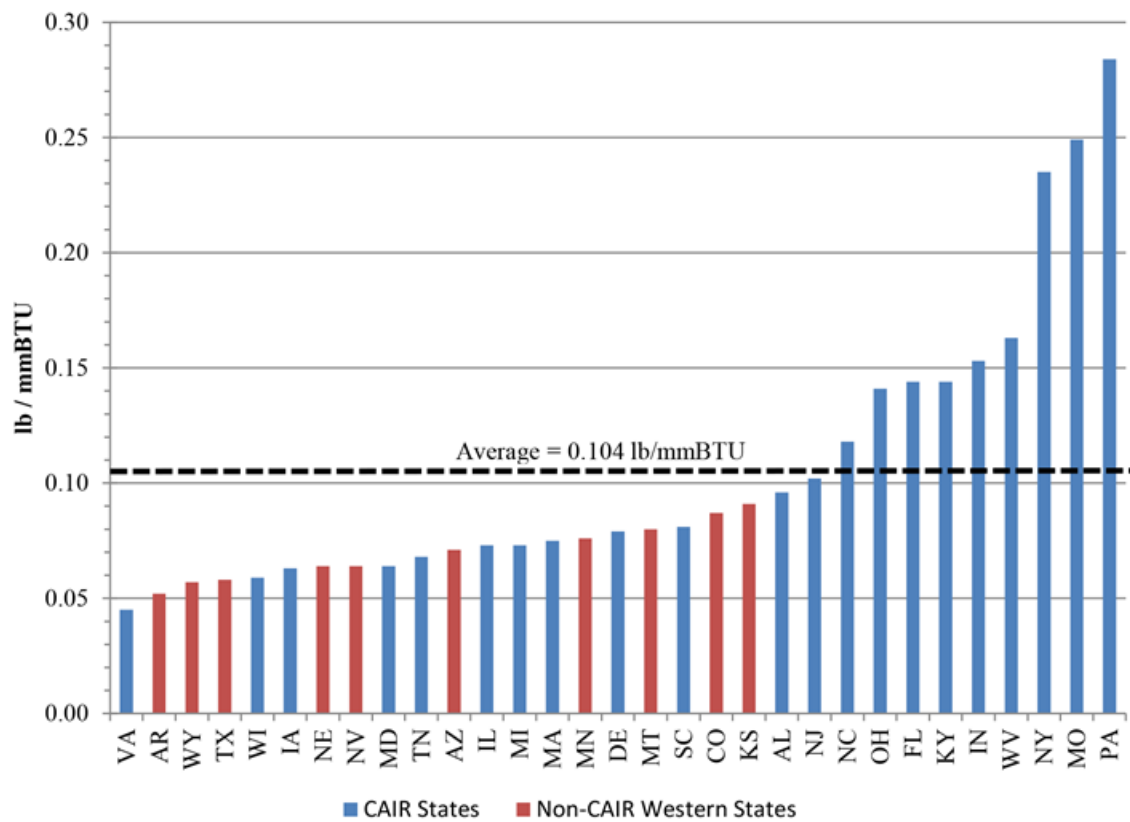


Figure 8. Average 2014 Ozone Season Statewide NO_x Emission Rates of SCR Coal EGUs.

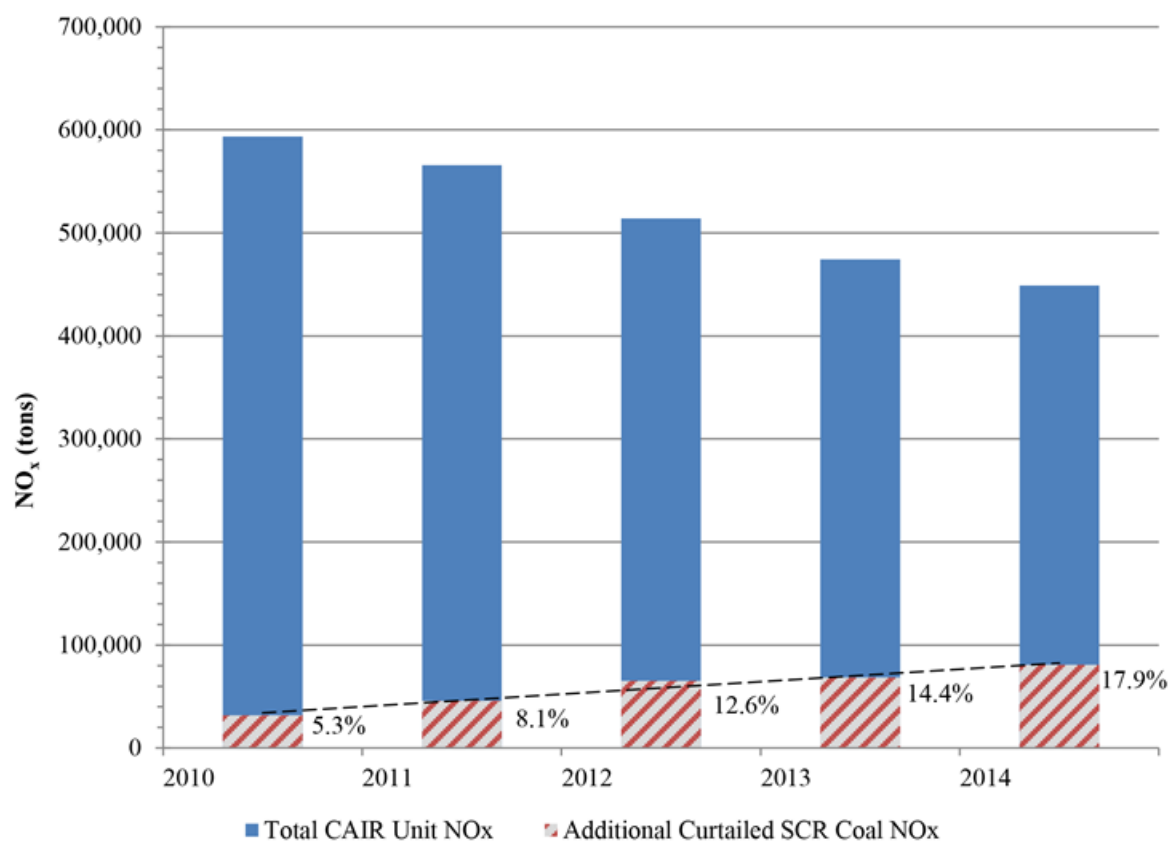


Figure 9. Ozone Season NO_x emissions in CAIR States with fraction due to SCR Coal curtailment and its percentage of total emissions.